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A Scientific Review of the Potential Environmental Effects of Aquaculture in Aquatic Ecosystems

Volume III

Near-field Organic Enrichment from Marine Finfish Aquaculture
(D.J. Wildish, M. Dowd, T.F. Sutherland and C.D. Levings)

Environmental Fate and Effect of Chemicals Associated with Canadian Freshwater Aquaculture
(R.J. Scott)

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FOREWORD

Context

The Government of Canada is committed to ensuring the responsible and sustainable development of the aquaculture industry in Canada. The Minister of Fisheries and Oceans' announcement of the $75 M Program for Sustainable Aquaculture (PSA), in August 2000, is a clear expression of this commitment. The objective of the PSA is to support the sustainable development of the aquaculture sector, with a focus on enhancing public confidence in the sector and on improving the industry's global competitiveness. Ensuring the sector operates under environmentally sustainable conditions is a key federal role.

As the lead federal agency for aquaculture, Fisheries and Oceans Canada (DFO) is committed to well-informed and scientifically-based decisions pertaining to the aquaculture industry. DFO has an ongoing program of scientific research to improve its knowledge of the environmental effects of aquaculture. The department is also engaged with stakeholders, provinces and the industry in coordinating research and fostering partnerships. As a contribution to the Federal government's Program for Sustainable Aquaculture, DFO is conducting a scientific review of the potential environmental effects of aquaculture in marine and freshwater ecosystems.

Goal and Scope

Known as the State-of-Knowledge (SOK) Initiative, this scientific review provides the current status of scientific knowledge and recommends future research studies. The review covers marine finfish and shellfish, and freshwater finfish aquaculture. The review focuses primarily on scientific knowledge relevant to Canada. Scientific knowledge on potential environmental effects is addressed under three main themes: impacts of wastes (including nutrient and organic matter); chemicals used by the industry (including pesticides, drugs and antifoulants); and interactions between farmed fish and wild species (including disease transfer, and genetic and ecological interactions).

This review presents potential environmental effects of aquaculture as reported in the scientific literature. The environmental effects of aquaculture activities are site-specific and are influenced by environmental conditions and production characteristics at each farm site. While the review summarizes available scientific knowledge, it does not constitute a site-specific assessment of aquaculture operations. In addition, the review does not cover the effects of the environment on aquaculture production.

The papers target a scientific and well-informed audience, particularly individuals and organizations involved in the management of research on the environmental interactions of aquaculture. The papers are aimed at supporting decision-making on research priorities, information sharing, and interacting with various organizations on research priorities and possible research partnerships.

Each paper was written by or under the direction of DFO scientists and was peer-reviewed by three experts. The peer reviewers and DFO scientists help ensure that the papers are up-to-date at the time of publication. Recommendations on cost-effective, targeted research areas will be developed after publication of the full series of SOK review papers.

State-of-Knowledge Series

DFO plans to publish 12 review papers as part of the SOK Initiative, with each paper reviewing one aspect of the environmental effects of aquaculture. This Volume contains two papers: Near-field organic enrichment from marine finfish aquaculture; and Environmental fate and effect of chemicals associated with Canadian freshwater aquaculture.

Further Information

For further information on a paper, please contact the senior author. For further information on the SOK Initiative, please contact the following:

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NEAR-FIELD ORGANIC ENRICHMENT FROM MARINE FINFISH AQUACULTURE

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EXECUTIVE SUMMARY

This paper reviews the literature on near-field organic enrichment associated with intensive marine finfish aquaculture. Fish farms are a source of suspended and dissolved organic matter, originating as fish feces, excess fish feed and net-cleaning wastes. The term "near-field" is used to differentiate between local (footprint limited) and more distant (far-field) effects, and refers to effects within the sedimentary footprint and between the population and community level. Near-field effects of mariculture are bounded by the physical limits of particulate waste dispersal and sedimentation from individual cages or farms.

PARTICLE TRANSPORT, DISPERSION AND BEHAVIOUR

To investigate the biogeochemical fate of organic matter in the benthic or pelagic ecosystem, it is necessary to understand how this material is transported and dispersed from the fish farm. Organic matter is transported from fish cages to the surrounding marine environment by the action of all types of water movements in the immediate vicinity of the cages. As this material moves, it spreads out and its concentration decreases, both by dilution and sedimentation.

Canadian coastal environments where aquaculture occurs are characterized by irregular coastlines and complex topography. Consequently, they often exhibit highly structured and quite complex flow fields. In strongly stratified marine systems, dissolved material can be effectively trapped in the upper or lower parts of the water column. In an aquaculture context, stratification can be an important factor in the dispersal of organic matter from certain farms in the inner portions of fjords in British Columbia.

Observational studies and numerical modelling are used to study transport and dispersion in the coastal zone. Observational studies of mixing often rely on the deployment of drifting buoys that mimic the movement of water parcels. Field experiments releasing coloured dye into the ocean are better able to characterize dispersion from a point source,

but these are often expensive, logistically difficult and environmentally sensitive. Numerical circulation models, based on a set of mathematical equations that govern fluid motion, provide a practical solution to the problem of coastal mixing.

In the water column, the behaviour of particles of organic matter is characterized by settling and deposition. Settling rate depends on the size, density and shape of particles. Stokes' law provides a basic framework for predicting the size dependence of particle settling. While discrete particles exhibit Stokes' settling behaviour, attractive forces also cause the formation of particle aggregates. Particle aggregation can effectively increase the settling flux of the original disaggregated particle mixture by repackaging small particles into larger, more rapidly sinking ones.

When particles settle from the water column, they may accumulate at the sediment-water interface or be subject to further transport and redistribution. When bottom shear stress exceeds a critical value, particles at the boundary between the sediment and water can be set in motion. Susceptibility to resuspension is set by a variety of sediment characteristics, including particle density and size, and degree of consolidation. Factors such as bioturbation have also been shown to effect erodibility of sediments (Andersen 2001). Numerical models are used to predict the temporal and spatial distribution of particulates in the marine environment.

ORGANIC ENRICHMENT AS A PROCESS

Organic matter flux of fish feces, waste feed and detached fouling organisms from cage surfaces, as well as natural particles, is monitored by measurements based on nitrogen or carbon in sedimentation traps. In the context of aquaculture, many authors examine carbon determined pyrolitically as a measurement of organic matter flux. However, the chemical and physical state of organic matter in sediments is not well understood. Thus, quantitative measures of total organic carbon are poor indicators of biochemical availability to biota.

The input of organic carbon to sediments, or sedimentation rate, is measured in suspended sediment traps. Reported sedimentation rates under and near salmon mariculture cages vary from 1 to 181 g $C \cdot m^{-2} \cdot day^{-1}$. Notwithstanding differences in environmental conditions, farm size and fish stocking densities, some of the variation in sedimentation rates is due to inherent difficulties in suspended sediment trap methodology. The benthic input from fish feces and waste feed can also be measured by mass balance calculations: based on total organic carbon accumulated in sediment, total input of fish feed, growth period and surface area of the cage footprint. However, all farm sites have some water movement and therefore require an examination of where the particles are deposited. Cromey et al. (2002) developed a particle tracking model that uses depth and particle settling rates as affected by observed currents with modelled shear velocity and turbulence.

In soft sediments receiving natural background levels of sedimentation (0.1 - 1.0 g $C \cdot m^{-2} \cdot day^{-1}$), the sediment-water interface is aerobic, and this aerobic layer contains abundant macrofauna and meiofauna. In contrast, soft depositional sediments receiving a continuous elevated level of sedimentation, for example due to fish feces and waste feed, become anoxic at the interface and develop a black, top-down sulfide layer. Some of the sulfide produced may also be oxidized by other chemoautotrophic bacteria (e.g. *Beggiaotoa* sp.) (Lumb and Fowler 1989). The white patches of this bacteria may be seen on the sediment surface under fish cages. Hargrave (1994) considered that flux rates of fish feces and waste feed of >1.0 g $C \cdot m^{-2} \cdot day^{-1}$ caused marked organic enrichment effects in net depositional sediments under salmon cages. The process of organic enrichment in farm footprints requires a varying amount of time to reach an equilibrium point, depending on oceanographic and substrate conditions. Some studies have shown that organic enrichment can be reversed if the increased levels of sedimentation are stopped (Brooks et al. 2003).

The initial effect of a sudden addition of a high flux of readily decomposable organic carbon to sediments is increased metabolism by aerobic bacteria, leading to hypoxia and anoxia causing death of the most susceptible aerobic life forms (Gray et al. 2002). In the fish cage footprint, the bulk of the metabolism is by sulfate reduction at a higher rate than at reference stations (Holmer and Kristensen 1992) and results in the loss of nitrification and denitrification pathways (Kaspar et al. 1988). The death of burrowing macrofauna leads to a rapid decline in the capability for irrigation or aerated water within the upper profile and a more rapid development of anoxia. The predominant bacteria become anaerobes, principally sulfate reducers and methanogenic bacteria. Methane makes up the bulk of the outgassing from heavily impacted farm sediments (Wildish et al. 1990), and sulfate reduction produces hydrogen sulfide, which is readily oxidized in aerobic seawater.

Organic enrichment indices may be regarded as proxies of the ecosystem to indicate extent or amount of organic enrichment. The most widely accepted index is based on macrofaunal species, abundance and biomass. Organic enrichment gradients by Pearson and Rosenberg (1978) and Poole et al. (1978) can be arbitrarily divided into four groupings based on the species and density of macrofauna present. Both of these older indices suffer because the macrofaunal or microbial surveys required to determine them are expensive in time to obtain. Other methods can be linked to spatial or temporal versions of the organic enrichment gradients based on macrofauna. They include sediment profile imaging (Rhoads and Germano 1986; Nilsson and Rosenberg 1997) and sediment geochemistry by redox and sulfide measurements (Wildish et al. 2001).

Hargrave (1994) proposed a benthic enrichment index based on the product of organic carbon and redox. The concept is to determine the sedimentation rate from the carbon present in interfacial sediments. Cranston (1994) described a geochemical method that is a direct measure of net carbon burial rates. The method is based on downcore concentrations of sulfate and ammonium, as indicators of the remineralization rates, and requires large cores and numerous, expensive chemical determinations. However, the method appears to be robust, and there is a positive linear relationship between sedimentation and carbon burial rates. Recently, Dell'Anno et al. (2002) suggested a suite of environmental variables to assess the organic enrichment status of the coastal zone in the Mediterranean sea, based on interfacial sedimentary variables.

ECOLOGICAL EFFECTS OF ORGANIC ENRICHMENT

Numerous reviews of organic enrichment associated with many industries show two important generalities: the ecological response is complex, involving pelagic-benthic coupling and both water column and sediments; and the effects include all sources of organic matter, both natural and anthropogenic.

Different physical and biological conditions on the Atlantic and Pacific coasts of Canada result in differing ecological responses to aquaculture. In the Bay of Fundy, the salmon aquaculture industry does not usually experience severe hypoxia in seawater because of energetic tidal mixing. If hypoxia occurs, it is in sediment pore water and localized to the benthic footprint area. There are few available data on dissolved oxygen in the sediments and water column near fish farms in British Columbia. However, naturally occurring low (<4 mg·L^{-1}) dissolved oxygen levels are present on the west coast of Vancouver Island and in Queen Charlotte Strait during the late summer and early fall (Levings et al. 2002). On the Pacific coast, fish farms are located over deeper and more diverse seabed habitats and most tenures include a mosaic of sediment types and are not characterized by homogenous level mud bottoms. Rock terraces, cliff walls and boulder fields are also under fish farms in some locations (see Levings et al. 2002 and references therein).

The general response of soft-sediment macrofaunal populations and communities to organic enrichment gradients is well established. It involves the local extinction of the resident equilibrium community, followed by the re-establishment of opportunists if conditions improve. Some species are more resistant to hypoxia than others (Diaz and Rosenberg 1995). In general, the crustaceans and echinoderms are most sensitive. Field studies suggest that, where seasonal hypoxia occurs, dissolved oxygen (DO) levels of 1 ml·L^{-1} begin to cause macrofaunal invertebrate mortality (Diaz and Rosenberg 1995). In areas of permanent oxygen deficiency, the benthic communities appear to be adapted to an even lower critical DO level. Although very low DO levels are seen as the major limiting factor for macrofauna, the role of H_2S (and ammonia) is less clear. Where severe hypoxia is present, both may be released.

Relatively little is known about the effects of organic enrichment on ecosystem functioning. Simplistic approaches to assess ecosystem effects assume that all of the secondary benthic production that becomes anoxic or hypoxic is lost to the next trophic level of predators. However, these approaches ignore that many individual predators are adapted to prey on a specific set of a few species in an equilibrium community.

Azoic or anoxic sediments could cause a significant shift in pelagic-benthic coupling. The effect of organic enrichment in sediments is to move the system to one dominated by bacteria, ciliates and meiofauna, and where the trophic links to the next level of the food web are broken. In bays heavily occupied by salmon farms, Pohle et al. (2001) analyzed the macrofaunal community at reference stations and found significant structural change.

While the cause could not be identified, the most probable explanation is that an aspect of enrichment linked to salmon farming caused changes in benthic-pelagic coupling in such a way as to exclude some species and encourage others. Although the severely hypoxic areas caused by fish farming in the Bay of Fundy are relatively small, no studies have examined benthic-pelagic coupling in the vicinity of fish farms.

TOWARDS PREDICTIVE MODELS

Prediction of benthic organic enrichment from fish farms requires the application of mathematical models. Process-oriented models use mathematical frameworks that describe the major physical and biogeochemical components and the processes through which they interact. Ocean circulation models predict the transport and mixing in the coastal zone, including the dispersion of organic matter from fish farms. Comprehensive ocean models, such as the Princeton Ocean Model (Blumberg and Mellor 1987) and the CANDIE ocean model (Sheng et al. 1998), have been successfully applied to coastal waters. Sediment transport models predict the time evolution of the spatial distribution of suspended particulate matter, as well as the exchanges of material between the water column and the benthos. Diagenetic models couple water column processes to vertically resolved sediment biogeochemical models (Wijsman et al. 2000).

Empirical models use statistical descriptions of the relationships between observable quantities that are indicators for key environmental components or processes. Findlay and Watling (1997) proposed an oxygen-based framework, based on the balance between benthic oxygen supply to oxygen demand, for assessing the benthic response to organic enrichment from salmon aquaculture. Dudley et al. (2000) developed a more process-oriented approach using a transport model to estimate dispersion of wastes from a fish farm to the benthos. DEPOMOD uses a hybrid approach to model benthic enrichment effects, and includes a particle tracking model and empirical relationships between the spatial distribution of solids and changes in benthic community structure (Cromey et al. 2002). In British Columbia, Carswell and Chandler (2001) and Stucchi (in prep.) have developed particle tracking models that give estimates of size of the sediment field under and near fish farms, but these models are not yet linked with benthic biological data.

TOWARDS METHODS OF MONITORING ORGANIC ENRICHMENT

Several variables to assess organic enrichment in seawater have been identified, including phytoplankton species and abundance matrices, dissolved oxygen concentrations, and total nutrient concentrations. Because none of these variables is accepted as the single indicator of the trophic status of seawater, multiparameter classifications have been used. For example, the OECD classification is based on chlorophyll a, plant nutrients and Secchi depths (Vollenweider and Kerekes 1982).

There are several methods to assess organic impacts in sediments. Those methods based on classical macrofaunal sampling and analysis are among the best known, although most costly. Alternative methods, such as sediment profile imaging or geochemistry, are more cost-effective. Recently developed methods, such as aerial photography, video photography and multibeam acoustics, have the potential to produce detailed and accurate maps over large areas. However, these methods require further research and groundtruthing. For benthic monitoring, the presence of predominantly hard or soft substrates will dictate the type of sampling. Other considerations include size of the ecosystem and the primary goal of the study.

General types of monitoring to detect organic enrichment in the marine environment are distinguished by their purpose. Geographical studies determining the limit of impact benefit primarily from synoptic survey methods, such as remote sensing of chlorophyll a in surface waters, underwater photography, video photography and acoustic surveys of soft sediments. Studies involving site comparison (treatment/reference sites), temporal trends (before/after) and practical monitoring (relative impact) can use a few alternative methods. Sediment profile images and sediment geochemical methods provide a much more cost-effective and credible alternative to the use of macrofaunal sampling and analyses for routine monitoring purposes.

RESEARCH NEEDS

Research is needed to provide an understanding of processes and to provide input to models and monitoring programs. Research is also needed to aid the scientific assessment of organic enrichment from marine finfish aquaculture (or near-field enrichment of marine finfish aquaculture). The following specific research needs are identified:

- Conduct sedimentology and physical and chemical oceanography studies, including coastal circulation, mixing, dispersion and transport processes in support of process models, and observation and modelling studies of water column particle dynamics.
- Conduct seasonal studies of organic enrichment (such as redox potential and sulfide) to examine ecological factors affecting organic enrichment events from salmon farming.
- Measure the availability of carbon to microbial decomposers.
- Determine effects of organic enrichment on coarse and hard substrates in British Columbia where fish farms are located over mosaics of sediment types.
- Determine effects of organic enrichment on ecosystem functioning to establish cause-effect relationships.
- Investigate how organic enrichment from aquaculture affects benthic-pelagic coupling.
- Undertake further fallowing studies in Pacific and Atlantic Canada.
- Verify models, such as Lagrangian-based particle models, sediment transport models and biogeochemical models, through collaborative efforts between modellers and field biologists.
- Predict holding capacity or assimilative limits related to the amount of local organic enrichment.
- Develop geographical survey methods, such as satellite, aerial surveillance, underwater video photography and acoustics.
- Devise new environmental monitoring methods.
- Calibrate, standardize and audit existing environmental monitoring methods.

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ENVIRONMENTAL FATE AND EFFECT OF CHEMICALS ASSOCIATED WITH CANADIAN FRESHWATER AQUACULTURE

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EXECUTIVE SUMMARY

The freshwater aquaculture industry in Canada is growing and with this growth comes the potential use of various chemical agents to treat water, fish or pathogens (e.g. fungicides, disinfectants, anesthetics, pigments, hormones and antibiotics). Despite the broad range of chemicals used in aquaculture around the world, only a subset is licensed for sale in Canada. This review considers chemotherapeutants actively used in Canadian freshwater aquaculture. Sixteen databases were searched for scientific publications on the environmental fate and effect of aquaculture chemotherapeutants. The majority of literature concerns marine systems, with few studies on freshwater aquaculture and only two directly examining freshwater aquaculture in Canada.

There are seven chemicals approved for sale when labeled for food fish use in Canada, including four antibiotic drugs (oxytetracycline, florfenicol, sulfadimethoxine plus ormetoprim, sulfadiazine plus trimethoprim), one anaesthetic (tricaine methanesulphonate) and two fungicides/disinfectants (formaldehyde and hydrogen peroxide) (Health Canada 2001a). Oxolinic acid has been included in this paper, although it is not currently used on Canadian aquaculture farms. However, this chemical is very widely used in salmonid culture outside of Canada, including the United States, and off-label prescription potential exists where veterinarians can legally prescribe it. In addition, oxolinic acid provides a wide degree of information regarding fate and effect data which could be relevant to other antibiotics.

Many studies have been published examining the fate and effect of antibiotics in marine systems, but few have been published with regard to the same issues in freshwater systems. As with all intensive animal husbandry, aquaculture practices create an opportunity for the proliferation and spread of pathogens that can lead to significant mortality of stock and subsequent loss of revenue (Dixon 1994). Antibiotics can be administered directly by injection or by releasing feed containing antibiotics directly into the aquatic ecosystem. Unconsumed medicated feed is available to wild animals. In addition, antibiotic-containing feed can accumulate in the sediments or unabsorbed antibiotics can be released in fish feces or urinary waste (Bjorklund and Bylund 1990, 1991), subsequently influencing the natural bacterial flora, an important component of ecological food webs. Thorpe et al. (1990) estimated that 1.4 to 40.5% of fish feed passed uneaten through an Atlantic salmon sea-cage. However, this may be a conservative estimate since diseased fish feed poorly (Bjorklund et al. 1990), and the majority of active form antibiotic passes unabsorbed through the gastrointestinal tract of fish (Cravedi et al. 1987; Bjorklund and Bylund 1991; Plakas et al. 1998). On the other hand, advances in feeding technology (e.g. underwater video; Foster et al. 1995) and alternative methods of incorporating antibiotic into feed (Duis et al. 1994) can affect the amount of antibiotic reaching the environment.

Nitrosomonas spp. and *Nitrobacter* spp. are important bacteria for nutrient cycling in freshwater trophic webs converting ammonia (toxic) to nitrate (non-toxic) (Ricklefs and Miller 2000), but in laboratory microcosms, oxytetracycline greatly inhibited the processing of ammonia (Klaver and Mathews 1994). During disease outbreaks in catfish ponds, the use of antibiotics cured the disease, but reduced bacterial conversion of toxic ammonia to nitrate, allowing ammonia to build up in pond sediments (Klaver and Mathews 1994).

The evolution of drug resistant strains of pathogenic bacteria is perhaps the most important implication of antibiotic use in aquaculture. Resistance to antibiotics is present in bacterial populations naturally (McPhearson et al. 1991; Johnson and Adams 1992; Spanggaard et al. 1993) and antibiotic use gives resistant strains the opportunity to proliferate and spread. Studies that examined antibiotic resistance following drug therapy at fish farms (Bjorklund et al. 1990, 1991; McPhearson et al. 1991; Nygaard et al. 1992; Samuelsen et al. 1992a; Spanggaard et al. 1993; Ervik et al. 1994; Kerry et al. 1996a; Herwig et al. 1997; Guardabassi et al. 2000) and in microcosms (Kerry et al. 1996; Herwig and Gray 1997; O'Reilly and Smith 2000) show an increased frequency of resistance to several drugs across a variety of bacterial species. However, Kapetanaki et al. (1995) and Vaughan et al. (1996) suggest that increased levels of bacterial drug resistance can arise independently of the presence of a drug (through sterile fish feed, sediments added to microcosm studies, uneaten fish food) and confound studies.

No published studies directly examined the environmental fate and effect of fungicides, disinfectants and anaesthetics within the scope of this review, but several studies have examined tissue deposition, toxicity and stress responses in fish in order to determine appropriate use rates for these chemicals in aquaculture practice (Xu and Rodgers 1993; Howe et al. 1995; Schreier et al. 1996; Rach et al. 1997a, b, 1998; Gaikowski et al. 1998, 1999; Keene et al. 1998; Jung et al. 2001).

In addition to the chemicals discussed above, carotenoid pigments (astaxanthin and canthaxanthin) are added to aquaculture feed to enhance flesh colour in cultured salmonids (Guillou et al. 1995; Metusalach et al. 1997). No studies have been published on the environmental fate and effect of carotenoid pigments introduced in fish feed. Carotenoid pigments could build-up in sediments since the molecules are non-water soluble and stable in the absence of light. Finally, salmonid production can be enhanced by culturing females only, a condition that manipulates the sex phenotype by exposing juvenile fish to 17 -alph-methyltestosterone either through immersion or incorporation in feed. No studies are available on the environmental fate or effect of this hormone within the scope of this review.

KNOWLEDGE GAPS

- Research is needed on the fate and effect of therapeutants in freshwater systems.

- Research is needed to identify the causal factors controlling the distribution, accumulation, and persistence of chemicals in freshwater.
- Research is needed regarding the factors affecting microbial resistance to antibiotics in freshwater.
- Research is needed to examine the chronic toxicity of antibiotics and other chemotherapeutants to fish and other freshwater organisms.
- There is a need to develop standard sampling design and analytical protocols in aquaculture science.
- There is a need for an inventory of therapeutant usage patterns that includes reports of what is used, where and in what amount.

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